

A Standards-Guided Multi-Criteria Decision Model for Preliminary Selection of UAV Outer-Shell Material Architectures

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ABSTRACT: This study presents a standards-guided multi-criteria decision model for preliminary selection of unmanned-aerial-vehicle outer-shell material architectures. Eleven printable polymers, fibre-reinforced thermoplastics, laminates, metals, and cellular systems are evaluated against twelve mechanical, impact, environmental, thermal, RF, manufacturing, repair, and lifecycle criteria. A transparent weighted-sum model is combined with evidence-confidence coding, mission-specific weight sets, one-way sensitivity analysis, and Monte Carlo uncertainty propagation. Under the explicitly bounded reference case, the PETG-CF lattice obtains the highest deterministic score (3.758/5), followed by continuous-fibre carbon-nylon (3.550/5) and a PETG/ABS honeycomb hybrid (3.500/5). The ranking is mission dependent: continuous-fibre and CFRP architectures lead stiffness-dominated cases, RF-transparent thermoplastics lead RF-sensitive enclosures, and aluminium leads the thermal/fire-constrained case. In 100,000 baseline simulations (score uncertainty $\sigma = 0.18$ and Dirichlet-distributed weights), PETG-CF ranks first in 93.84% of trials; its simulated mean score is 3.748, standard deviation 0.086, and 95% interval 3.579–3.914. These results are model-based screening outcomes, not empirical qualification. The model therefore recommends hybrid, function-zoned shells and specifies the coupon-, panel-, and shell-level tests required before design release.

Keywords: UAV, outer shell, material architecture, MCDA, weighted-sum model, uncertainty analysis, additive

manufacturing, standards-based validation



1. INTRODUCTION

The outer shell of a small- or medium-sized UAV/UAS is often considered to an auxiliary enclosure component. In practice, it is a multifunctional engineering subsystem that contributes to local stiffness, landing and handling-load transfer, protection of batteries and electronic payloads, energy dissipation of impact force, ultraviolet and moisture shielding, and RF compatibility when conductive composites or metals are located near antenna [1].

Thus, optimizing by density or stiffness alone is insufficient. At high stiffness, all-composite construction may result in structure that is statically efficient but raises questions of production, repair, tooling cost, life cycle and brittleness; at low stiffness, printable thermoplastic composites may be cheap and repairable but may suffer from heat-deflection temperature, flammability, dimensional stability, and long-term ultraviolet exposure [2].

The primary design problem this work seeks to address is the lack of a selection method with auditable traceability from heterogeneous evidence to mission-specific design decisions, particularly material-architecture selection. This is required at early design stages, when there is a lack of data at coupon, panel, and shell levels and many design team members are unaware of what has been experimentally validated, what the data implies, and why. This paper presents in-particular the establishment of a design method for composite structures in a UVF. It is shown that a systematic approach exists to support a design team in determining material-structure

UAV shell design is reformulated as stakeholder-informed, function-oriented materials engineering. The structure is decomposed and evaluated by function: load paths, external skins, crash absorbers, antenna windows, heat-spreading or

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threaded interfaces, and replaceable repair modules. Candidate designs, including advanced high-modulus FFRPs, are scored in a transparent multiple-criteria decision analysis (MCDA) model under a bounded reference mission and several alternative mission emphases. A weight-value approach is used to quantify stakeholder priorities, and measures of scoring and MCDA uncertainty, as well as sensitivity analysis, are calculated to assess plausibility. A reference, trade-off diagram and its boundary are used for validation. The reference mission is defined, and the role of a UAV shell is described as a multifunctional structure, including load-bearing, crash-absorbing, structural-interfacing, thermal-spreading, environmental-sealing and antenna elements. The properties, common design goals and current designs of these functions are reviewed, and a challenge case structure is identified. Brief descriptions of advanced FFRP and advanced ceramic material systems are provided. Scientific novelty and contributions. The methodological novelty lies in integrating functional-zone decomposition, auditable evidence-coded scoring, mission [3].

2. Literature Review

Recent literature indicates a rapid increase of research activity on drones and small-airframe utilizing fused-filament fabrication, chopped-fiber reinforced thermoplastics, continuous-fiber reinforced nylon/Onyx systems, topology-optimized frames, and composite laminates. These papers are interesting as they provide quantified tensile, flexural, impact or frame-level responses through selected material-process combinations [4].

PETG-CF and related composite filaments have been studied for frame and shell-relevant applications because infill architecture can substantially affect tensile response, impact absorption, hardness, and drop behavior. Thermoplastics reinforced by continuous fibers have better specific stiffness and strength when the fibers run along load paths; nevertheless, their performance depends greatly on fiber orientation, fiber routing, fiber consolidation, moisture preconditioning, and concentration of stresses in local areas. CFRP laminates keep structural efficiency high, but their tooling, repair, RF effects, and recyclability pose additional concerns in design [4,5].

Another finding in the existing body of knowledge is that the design of internal structure can be just as important to a part's efficiency as material choice. Sacrificial regions made of honeycomb and lattice structures absorb energy by crushing in certain directions, whereas topology optimization and generative design allocate materials around load paths instead of uniformly spreading them out [6-9].

In the outdoors, UAVs face ultraviolet light, water, salt, dust, thermal cycling, and chemicals. The properties of FFF plastics and high-performance thermoplastics can change after environmental conditioning, so no shell design based on unaged test data is valid [10].

The radio frequency (RF) function is another design constraint. RF-sensitive antennas inside carbon-fiber or metal shells can be attenuated or detuned by GNSS, telemetry, Wi-Fi, or remote-control radio-frequency communication functions, unless RF-transparent windows or sufficient separation distance are provided. Thus, an exceptionally strong shell might not satisfy a compact RF-sensitive UAV if it is surrounded by conductive continuity.

Fireproofing and thermal protection are more UAV requirements, where certain shell materials close to the batteries, electronic speed controllers, motors, or the current conductors need heat reflection or shielding, thermal testing, and flammability tests. However, it doesn't mean that all thermoplastics are not used in the UAVs but in correct selection, location, and thermal isolation [11].

Lifecycle assessment (LCA) is an important step in the design of electric UAVs. While not consuming fuel, they at least require energy in the manufacturing process as well as the transportation and assembly. The replacement frequency, reparability and disposal route may also have an impact on the environmental impact. Added benefit in terms of mass saving would justify the usage of high energy demanding composite materials, if it improves their operating or service time; otherwise a material choice such as thermoplastics can be taken under consideration, because of their reparability and recyclability [12-15].

The development of composite materials has been driven by the benefits that they provide and is associated with built-in challenges such as end-of-life (EoL) management and formal definition of sustainability. Their advantages and disadvantages are examined in the context of Medium and Small-sized Unmanned Aerial Vehicles (MSUAVs), and the sustainability of palm oil fibre-nucleated polyamide resin as a material for UAVs is discussed. Results demonstrate that the use of composites in UAVs, in particular the anticipated decrease in fossil resource input costs, can be achieved by bio-based and natural-fibre composites. However, research on the use of such materials must also be carried out in the context of UAVs due to its high sensitivity to moisture, limited durability, restricted fibre-matrix compatibility, variability in supply and lack of information on EoL options. Basalt-fibre composites and composites made of recycled polymers are also discussed as candidate materials for MSCAs, as these can potentially address impact tolerances, cost pressures and sustainability in a circular economy sense. In addition, recycled-composite spars demonstrate that structural aerospace-like components may be fabricated via a low-cost, low-shear vacuum-bag route and yet allow for remelting and reshaping. Overall, these families [16,17].

Research into multifunctional mechanical metamaterials is shaping a different route: a geometry designed for impact attenuation, tunable stiffness, vibration control, or thermal/RF functions. Experimentally validated chiral multi-curved shell metamaterials exhibit smooth energy-absorption plateaus and repeatable drop-impact attenuation. Drone lifecycle reviews also emphasise that material production, battery needs, service life, damage and lifecycle must be assessed under a common mission-based functional unit with the same ontology of application. These new validations definitively

confirm the model's high-level, but also highlight an ongoing need for geometry- and process-matched experiments [18,19]. The principal literature streams and the remaining research gap are summarized in Table 1.

Table 1 Literature streams and the gap addressed by the revised model

Evidence stream	What it contributes	Remaining gap addressed in this paper
Material testing studies	Tensile, flexural, impact, infill, or frame-level results for selected materials	Often limited to one material/process family; not directly translated into shell-zone selection
Topology/generative design studies	Mass reduction and load-path optimization	Usually emphasize structural efficiency; RF, fire, repair, and LCA are less integrated
Composite laminate literature	High specific stiffness and aerospace precedent	Repair, tooling, RF attenuation, and lifecycle impacts complicate small-UAV use
Standards and qualification protocols	Reliable methods for tensile, flexural, impact, UV, fire, and LCA testing	Standards specify measurement; they do not rank mission-specific shell architectures
MCDA/AHP engineering studies	Transparent decision structures for multi-attribute problems	Require careful distinction between measured data, expert judgment, and uncertainty

The gap is therefore not the absence of candidate materials. The gap is the absence of a transparent model that combines material evidence, shell function, mission weighting, uncertainty treatment, and standards-based validation in a single preliminary-selection workflow. The bounded reference design basis used by the model is specified in Table 2.

Table 2 Reference design basis used to bound the MCDA model

Item	Definition
Platform class	Small-to-medium electric UAV shell; multirotor or compact fixed-wing shell regions
Decision level	Preliminary material-architecture screening before full coupon, panel, and shell qualification
Primary shell functions	Protection, local support, impact attenuation, vibration control, environmental resistance, RF compatibility, repairability
Excluded from ranking	Detailed aerodynamic shape optimization, motor-arm structural sizing, certified airworthiness qualification, and full cost accounting
Decision output	Mission-bounded candidate ranking plus zone-specific architecture recommendation
Validation output	Test matrix specifying measurable properties needed before design release
Reference mass and payload (model boundary)	Illustrative 5.0 kg maximum take-off mass and 1.5 kg payload; these are declared screening assumptions, not measurements from a prototype.
Shell envelope and mass target	Approximate $0.60 \times 0.45 \times 0.18$ m enclosure; preliminary shell-mass target ≤ 0.75 kg.

Item	Definition
Reference impact condition	Hard-landing screening case equivalent to a 1.0 m vertical drop, subject to later shell-level instrumented verification.
Reference mission duration	Nominal 30 min electric mission; endurance-sensitive scenarios are assessed separately.

Table 3 Candidate systems are grouped by architecture and shell function, not by material name alone

Class	Examples in the model	Primary shell role
Printable thermoplastic skins	PLA, ABS, PETG, ASA	Low-cost shells, weather skins, antenna covers, replaceable panels
Short-fiber reinforced thermoplastics	PA-CF short-fiber	Semi-structural printed brackets, ribs, stiffened local panels
Continuous-fiber reinforced thermoplastics	CFF carbon-nylon	Motor bridges, ribs, inserts, load-oriented reinforcement paths
Composite laminates	CFRP laminate	High-stiffness load paths, premium skins, endurance-oriented structures
Light metal inserts or local panels	Al 6061-T6, Mg AZ31	Threaded interfaces, heat spreaders, protected metal features
Cellular crash architectures	PETG-CF lattice; PETG/ABS honeycomb	Sacrificial energy absorbers, corner modules, battery/camera protection zones

The classification presented in Table 3 resolves a major comparability problem. A lattice and a laminate are not equivalent material forms; they are different shell architectures. Therefore, the ranking is interpreted as a mission-specific suitability score for an architecture-role pair, not as a universal hierarchy of materials.

3. Methodology

The model utilizes a compensatory weighted-sum model (WSM). For material architecture i , the aggregate score is S_i , where x_{ij} is the normalized 1-5 score for criterion j , and w_j is the weight, with $\sum_{j=1..m} w_j = 1$. The WSM was selected as the decision model because the initial dataset is heterogeneous, containing measurements, findings, and engineering judgments, while the additive model is easily interpretable, auditable, and updateable. The rationale for the selection of weights is discussed below. The method is not AHP, because pairwise-comparison surveys have not been performed.

Weight rationale. The reference vector represents a design-policy preference vector for the bounded UAV in Table 2, not a statistically estimated preference vector. The impact energy absorption has 14% because energy management during hard landing and payload protection belong to the shell's primary functions; specific stiffness and strength have 13 and 12%, respectively; environmental resistance accounts for 10%; damping and manufacturability – 8% each; thermal, RF, fire, assembly, repairability, and lifecycle criteria – 7% each. The weights were selected on the basis of the functional decomposition in Table 4, and verification requirements linked to relevant standards. Next, the weights were evaluated for sensitivity to extreme missions, $\pm 20\%$ one-sided perturbations of the design variables, and joint perturbations using stochastic methods.

Method selection rationale. AHP is an appropriate method when expert judgments are available; however, it would be necessary to report pairwise comparisons and their consistency. TOPSIS, VIKOR, PROMETHEE, and ELECTRE methods are also viable if non-compensatory criteria and preference thresholds are present; these methods are based on the proximity to an ideal solution, or pairwise outranking. By contrast, WSM is utilized because of the need to maintain traceability and facilitate recalculations, and the lack of confidence in the initial dataset to define preference thresholds. The comparison of final rankings produced by different methods is a subject of future work [20,21].

$$S_i = \sum_{j=1..m} w_j x_{ij}, \quad \text{with} \quad \sum_{j=1..m} w_j = 1 \quad (1)$$

For measured benefit-type criteria, where larger values are preferred, the normalized score is $x_{ij} = 1 + 4(y_{ij} - y_{j,min})/(y_{j,max} - y_{j,min})$, where y_{ij} is the measured value for alternative i, and $y_{j,min}$ and $y_{j,max}$ are the minimum and maximum comparable values for criterion j.

$$x_{ij} = 1 + 4 \cdot \frac{(m_{ij} - m_{j,min})}{(m_{j,max} - m_{j,min})} \quad (2)$$

For cost-type or adverse criteria, where smaller values are preferred, the normalized score is $x_{ij} = 1 + 4(y_{j,max} - y_{ij})/(y_{j,max} - y_{j,min})$. If $y_{j,max} = y_{j,min}$, all alternatives receive the neutral score 3 to avoid division by zero. $S_i, w_j, x_{ij}, y_{ij}, i$, and j are defined at first use; $\sum_j w_j = 1$.

$$x_{ij} = 5 - 4 \cdot (m_{ij} - m_{j,min}) / (m_{j,max} - m_{j,min}) \quad (3)$$

Table 4 Functional requirement decomposition for UAV shell architecture selection

Requirement cluster	Engineering meaning	Primary measurable outputs
Mechanical support	Payload, battery, motor-interface, landing, and handling loads	Specific stiffness; specific strength; fatigue screening
Impact protection	Hard landing, collision, corner strike, battery/camera protection	Peak force; absorbed energy; damage area; residual function
Vibration/acoustic control	Motor excitation, sensor noise, camera stability	Natural frequencies; damping ratio; transmissibility
Environmental resistance	UV, moisture, salt, dust, oils, agrochemicals, thermal cycles	Property retention after aging; coating adhesion; dimensional drift
Thermal/fire safety	Battery proximity, motor/ESC heat, thermal runaway exposure	HDT/thermal cycling; UL 94 class; dripping behavior
EMI/RF performance	GNSS, telemetry, Wi-Fi, control link, antenna placement	Signal attenuation; antenna detuning; link budget change
Manufacturing and assembly	Printing, lay-up, machining, inserts, bonding, fastening	Tolerance, repeatability, tooling, unit cost, repair module replacement
Lifecycle performance	Mass, replacement rate, manufacturing energy, recyclability	Functional-unit burden; replacement rate; end-of-life pathway

When directly comparable measurements are available, the benefit- and cost-type normalization equations are applied; otherwise, an evidence-coded rubric score is assigned to the comparison. It is then essential to interpret the score in the context of the scoring rubric in Table 5 and the evidence class in Table 6 and criterion-level provenance of the comparison. For instance, E1 indicates that the tests compared are directly comparable, whereas E2 applies to related but not identical tests. E3 is used when material behavior is established, and E4 is used when a validation requirement lacks direct evidence. The E2-E4 classifications are engineering screening judgments rather than universal constants and therefore subject to uncertainty analysis.

Table 5 Auditable 1-5 scoring rubric

Score	Interpretation	Operational rule
5	Excellent suitability	Direct experimental evidence or strong material consensus supports top-tier performance for the shell function
4	High suitability	Performance is consistently strong but depends on process control, mission conditions, or local design measures

Score	Interpretation	Operational rule
3	Moderate suitability	Usable with design controls such as ribs, coatings, inserts, isolators, or hybridization
2	Low-to-moderate suitability	The criterion is a design-control issue and requires substantial mitigation
1	Low suitability	The criterion conflicts with ordinary shell requirements unless major redesign is introduced

Table 6 Evidence traceability classes used to avoid treating all scores as equally certain

Class	Evidence type	Traceability condition	How used
E1	Directly comparable test data	Same or close specimen geometry, process, conditioning, and property unit	Primary score input
E2	Comparable but not identical data	Same material family or architecture with different printer, lay-up, infill, environment, or geometry	Score input with uncertainty
E3	Consensus material behaviour	Well-established material property trend or standard engineering expectation	Rubric score with conservative interpretation
E4	Validation-planning criterion	Criterion required by function but not sufficiently measured in the source set	Included in test matrix and uncertainty scenario

The stochastic score used in Monte Carlo trials is defined as:

$$x_{ij}^r = \text{clip}[x_{ij} + \varepsilon_{ij}^r, 1, 5], \quad \varepsilon_{ij}^r \sim N(0, \sigma^2) \quad (4)$$

Monte Carlo implementation. For the baseline analyses, we use 100000 trials and a fixed random seed for reproducibility. Each score is independently perturbed according to a truncated normal model, $x_{ij}^r = \text{clip}[x_{ij} + \text{epsilon}_{ij}^r, 1, 5]$, where $\text{epsilon}_{ij}^r \sim N(0, \sigma^2)$ and $\sigma = 0.18$ score points. The score error incorporates both evidence and manufacturing-process uncertainty at the screening level, reflecting realistic variability due to printing orientation, infill, fibre routing, moisture conditioning, and process control, but is not calibrated to a particular process capability distribution. We sample weights from a Dirichlet distribution with mean equal to the reference vector and total concentration $\alpha_0=100$. In sensitivity analyses, we use $\sigma = 0.10$ and 0.30 score uncertainty. All results are reported as first rank probabilities, means, and standard errors, together with percentile-based 95% uncertainty intervals. The reference and scenario-specific weighting schemes are reported in Tables 7 and 8.

Table 7 Reference weighting scheme for the bounded small-UAV shell case

Criterion	Weight	Weight (%)
Specific stiffness	0.13	13.00
Specific strength	0.12	12.00
Impact energy absorption	0.14	14.00
Vibration/acoustic damping	0.08	8.00
Environmental resistance	0.10	10.00
Thermal/heat tolerance	0.07	7.00
EMI/RF compatibility	0.07	7.00
Flammability safety	0.06	6.00
Manufacturing feasibility / unit cost	0.08	8.00

Criterion	Weight	Weight (%)
Joining/assembly	0.05	5.00
Reparability	0.05	5.00
Lifecycle sustainability	0.05	5.00

Table 8 Scenario-specific weights used to test whether rankings are mission dependent

Criterion	Reference small-UAV shell	Crash/repair dominated	Stiffness/load-path dominated	RF-sensitive enclosure	Thermal/fire constrained
Specific stiffness	0.13	0.09	0.22	0.08	0.08
Specific strength	0.12	0.08	0.20	0.07	0.08
Impact energy absorption	0.14	0.22	0.10	0.10	0.10
Vibration/acoustic damping	0.08	0.08	0.04	0.08	0.05
Environmental resistance	0.10	0.09	0.08	0.10	0.09
Thermal/heat tolerance	0.07	0.06	0.08	0.06	0.16
EMI/RF compatibility	0.07	0.06	0.04	0.22	0.06
Flammability safety	0.06	0.05	0.04	0.06	0.16
Manufacturing feasibility / unit cost	0.08	0.10	0.06	0.08	0.07
Joining/assembly	0.05	0.06	0.05	0.05	0.05
Reparability	0.05	0.08	0.03	0.05	0.04
Lifecycle sustainability	0.05	0.03	0.06	0.05	0.06

The proposed validation campaign is anchored to the applicable tensile, flexural, impact, residual-strength, ultraviolet-weathering, and flammability standards [22-26]. The corresponding standards-based validation matrix is presented in Table 9.

Table 9 Proposed validation matrix for transforming preliminary selection into an evidence-complete qualification campaign

Domain	Protocol/standard	Measured outputs	Reporting rule
Tensile behavior	ASTM D638 / ISO 527 for polymers; ASTM D3039 for oriented laminates	Ultimate strength, modulus, elongation, failure mode	n >= 5; report orientation, conditioning, print parameters, lay-up, and rate
Flexural behavior	ASTM D790	Flexural modulus, flexural strength, failure mode	Report span, loading rate, specimen geometry, and conditioning

Domain	Protocol/standard	Measured outputs	Reporting rule
Low-velocity impact	ASTM D7136/D7136M for laminates; instrumented shell-representative drop tests for printed shells	Peak force, absorbed energy, force-time curve, dent depth, damage area	Use support conditions representative of UAV shell zones
Compression after impact	ASTM D7137/D7137M where laminate panels apply	Residual compressive strength	Report impact energy and damage state
Modal response	Impact hammer or shaker modal test	Natural frequencies, damping ratio, transmissibility	Compare with motor excitation bands and camera/sensor requirements
UV/weathering	ASTM G154 or equivalent	Mass, color, tensile/flexural retention, crack development	Report irradiance, cycle, temperature, and exposure hours
Moisture/salt/chemical exposure	Immersion, salt-fog, or mission-specific chemical exposure followed by retesting	Moisture uptake, dimensional drift, property retention	Required for marine, coastal, or agricultural UAVs
Thermal/fire response	Heat-deflection/thermal cycling plus UL 94 where enclosure safety is relevant	Dimensional stability, softening, burn rating, dripping behavior	Required near batteries, ESCs, motors, and power electronics
EMI/RF behavior	Antenna gain, RSSI, GNSS reception, and link-budget tests with representative enclosure geometry	Signal attenuation, detuning, range impact	Required for conductive composite or metal-continuous shells
FEA correlation	Coupon-to-panel-to-shell model updating	Correlation of stiffness, mode shape, impact response, stress hot spots	Report boundary conditions, mesh convergence, material models, and validation error
Lifecycle assessment	ISO 14040/14044-compatible functional unit and inventory	kg CO ₂ -eq per shell or mission-hour; replacement rate; end-of-life path	Report boundary, database, impact categories, and sensitivity assumptions

As shown in Table 10, the index uses conventional FDM thermoplastic production as 1.0 and compares relative process burden only [27]. It excludes labour-rate, energy-price, batch-size, scrap, tooling-amortization, and regional supplier effects. Therefore, procurement quotations and a defined production volume are required before lifecycle-cost decisions.

Table 10 Preliminary manufacturing-economics screen (relative, not supplier quotations)

Architecture family	Relative unit-cost index	Principal cost drivers	Interpretation
FDM thermoplastics (PLA/ABS/PETG/ASA)	1.0–1.5	Filament, machine time, support removal	Lowest tooling burden; suitable for low-volume replaceable shells
Short-fibre printed thermoplastics	1.4–2.2	Filled filament, nozzle wear, drying, process control	Moderate premium for stiffness and durability
Continuous-fibre printed composite	2.5–4.0	Reinforcement, proprietary equipment, fibre routing	Higher part and process cost; reserve for load paths

Architecture family	Relative unit-cost index	Principal cost drivers	Interpretation
CFRP laminate	3.0–5.0	Tooling, lay-up, cure, trimming, inspection	Economically justified mainly by structural efficiency or volume
Machined/form Al/Mg local features	2.0–4.5	Stock, machining/forming, coating, joining	Best restricted to inserts, heat spreaders, or protected zones
Printed honeycomb/lattice modules	1.2–2.0	Long print time, quality checks, replaceable-module design	Attractive for sacrificial crash zones at low volume

4. Results

4.1 Reference Ranking

The three methods identified the PETG-CF lattice as rank 1 and the CFF carbon-nylon as rank 2. The WSM and VIKOR techniques also ranked the PETG/ABS honeycomb hybrid third while the TOPSIS technique ranked the CFRP third due to its proximity to the ideal solution in terms of mechanical criteria. The Spearman rank correlation coefficients were also very close (WSM–TOPSIS $\rho = 0.936$; WSM–VIKOR $\rho = 0.982$; TOPSIS–VIKOR $\rho = 0.918$). Therefore, the best option was not identified uniquely by the WSM, although the intermediate ranks may be inconsistent across methods. The VIKOR method used $v = 0.50$, and all methods employed the same benefit-type 1–5 matrix and reference weights. The detailed reference ranking and cross-method comparison are reported in Tables 11 and 12, while Figure 1 visualizes the weighted MCDA ranking.

Table 11 Reference small-UAV shell ranking under the bounded MCDA model

Material system	Rank	Weighted score / 5	Primary interpretation
PETG-CF lattice	1	3.758	Reference shell and crash-zone candidate
CFF carbon-nylon	2	3.550	Load-path and rib candidate
PETG/ABS honeycomb hybrid	3	3.500	Sacrificial absorber and RF-transparent crash zone
CFRP laminate	4	3.431	Premium high-stiffness load-path candidate
ASA FDM	5	3.396	Outdoor skin and weather enclosure candidate
PETG FDM	6	3.391	Cost-effective repairable outdoor shell
PA-CF short-fiber	7	3.347	Stiff printed semi-structural support
Al 6061-T6	8	3.284	Threaded insert and heat-spreader candidate
ABS FDM	9	3.065	Serviceable secondary shell
Mg AZ31	10	2.959	Specialized lightweight metal candidate with controls
PLA FDM	11	2.615	Indoor prototype and educational shell

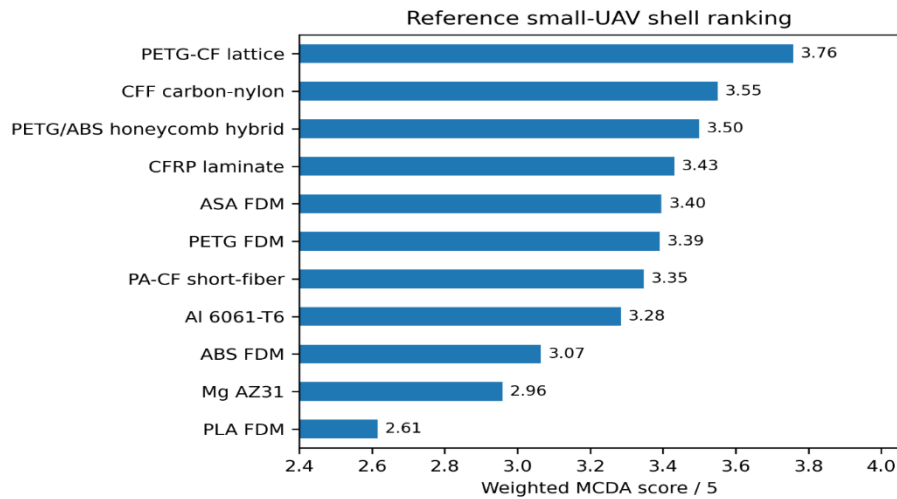


FIGURE 1 Reference weighted MCDA ranking. The ranking is a bounded model result, not a universal material hierarchy

In the bounded reference model, the PETG-CF lattice ranks first because the declared weights favour impact absorption, manufacturability, repair, and acceptable RF behaviour. CFF carbon-nylon and CFRP score more strongly for load-path efficiency but incur RF, repair, and manufacturing penalties. This is a conditional model interpretation; it does not establish that PETG-CF is mechanically superior or optimal for every UAV application.

Table 12 Comparison of WSM, TOPSIS, and VIKOR rankings under the same score matrix and weights

Material architecture	WSM	Rank	TOPSIS C_i	Rank	VIKOR Q_i	Rank
PLA FDM	2.615	11	0.284	11	1.000	11
ABS FDM	3.065	9	0.377	10	0.613	9
PETG FDM	3.391	6	0.473	8	0.464	7
ASA FDM	3.396	5	0.482	7	0.422	6
PA-CF short-fiber	3.347	7	0.515	5	0.365	5
CFF carbon-nylon	3.550	2	0.620	2	0.162	2
CFRP laminate	3.431	4	0.597	3	0.360	4
Al 6061-T6	3.284	8	0.485	6	0.507	8
Mg AZ31	2.959	10	0.403	9	0.699	10
PETG-CF lattice	3.758	1	0.638	1	0.000	1
PETG/ABS honeycomb hybrid	3.500	3	0.533	4	0.347	3

Table 13 Scenario-specific top-three rankings

Scenario	Rank 1	Rank 1 score	Rank 2	Rank 2 score	Rank 3	Rank 3 score
Reference small-UAV shell	PETG-CF lattice	3.758	CFF carbon-nylon	3.550	PETG/ABS honeycomb hybrid	3.500
Crash/repair dominated	PETG-CF lattice	3.921	PETG/ABS honeycomb hybrid	3.702	PETG FDM	3.510
Stiffness/load-path dominated	CFF carbon-nylon	3.899	CFRP laminate	3.835	PETG-CF lattice	3.706
RF-sensitive enclosure	PETG/ABS honeycomb hybrid	3.755	PETG-CF lattice	3.720	ASA FDM	3.718
Thermal/fire constrained	Al 6061-T6	3.647	PETG-CF lattice	3.474	CFF carbon-nylon	3.425

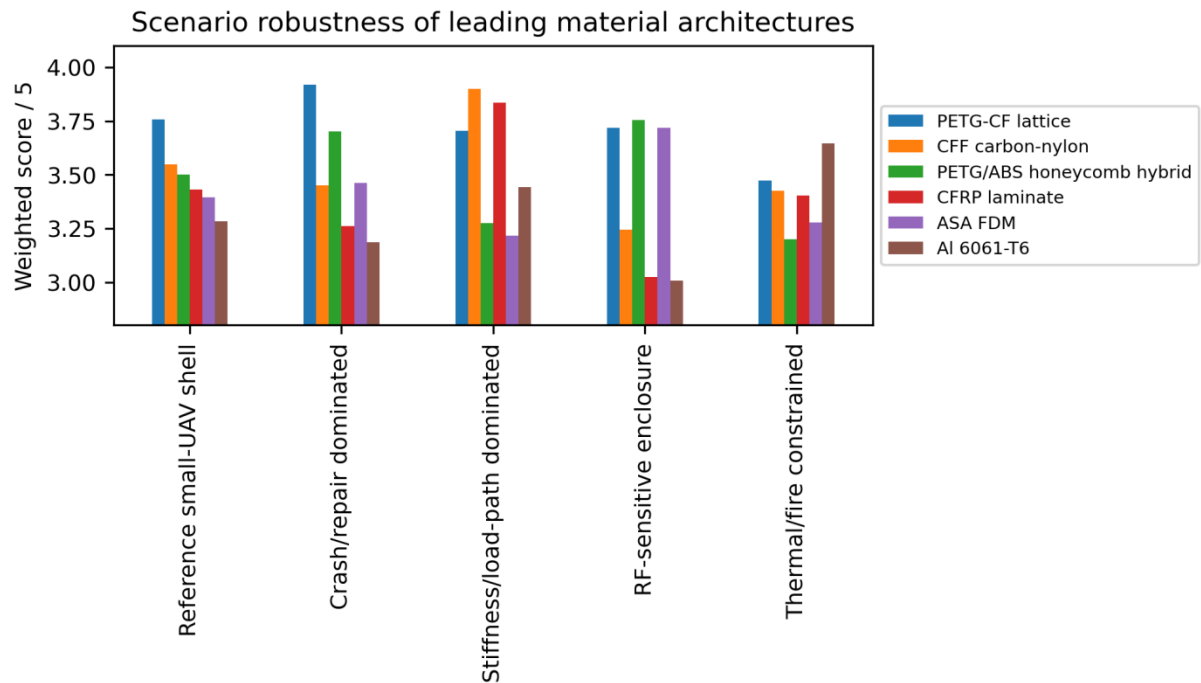


FIGURE 2 Scenario comparison confirms that the preferred material architecture changes when the mission emphasis changes

Table 14 Mission-specific material-selection rules derived from the revised model

Mission class	Dominant requirement	Recommended architecture	Design rule
Racing / training drones	Crash energy absorption, quick replacement, low mass	PETG-CF lattice shell with replaceable PETG/ABS honeycomb corner zones and CFF reinforcements at motor mounts	Prioritize sacrificial deformation and modular repair

Mission class	Dominant requirement	Recommended architecture	Design rule
Aerial photography / survey	Vibration isolation, dimensional stability, camera protection	ASA/PETG skin with damping pads; CFF ribs only where payload loads require stiffness	Separate camera natural frequencies from motor excitation bands
Marine / coastal inspection	Moisture, salt, UV, seal integrity, post-aging ductility	ASA/PETG weather shell with protective coating; high-performance polymers only after aging validation	Retest tensile/flexural retention after UV/salt exposure
Delivery / cargo UAVs	Payload load paths, battery safety, landing impact	CFF carbon-nylon or CFRP load frame with PETG/ABS honeycomb energy absorbers	Use controlled crush zones to reduce peak transmitted force
Agricultural drones	Chemical exposure, mud, water, field repair	PETG/ASA replaceable panels with chemical-resistant coating and sealed fasteners	Design panels for washing, replacement, and coating renewal
Long-endurance UAVs	Mass efficiency, stiffness, aerodynamic cleanliness, lifecycle burden	CFRP laminate or continuous-fiber optimized shell with early lifecycle screening	Use high-footprint composites only where mass savings translate into mission-hour benefit
RF-sensitive compact UAVs	GPS/telemetry reliability and antenna integrity	RF-transparent PETG/ASA antenna windows integrated into composite or metal structures	Avoid uninterrupted conductive enclosures around antennas
Thermal/fire-constrained zones	Battery, ESC, motor, or high-current proximity	Local Al 6061-T6 heat spreaders, shields, or inserts combined with isolated polymer skins	Separate heat-spreading function from RF-transparent and crash-absorbing functions

Table 15 One-way sensitivity summary

Sensitivity output	Result
One-way perturbations tested	24
Reference top candidate	PETG-CF lattice
PETG-CF first-rank cases	24/24
Minimum margin to runner-up	0.170
Most competitive perturbation	Specific stiffness +20%
Closest runner-up in that perturbation	CFF carbon-nylon

Table 16 Monte Carlo first-rank probability under simultaneous weight and score uncertainty

Material system	First-rank probability (%)
PETG-CF lattice	95.015
CFF carbon-nylon	4.130
CFRP laminate	0.505
PETG/ABS honeycomb hybrid	0.215

Material system	First-rank probability (%)
Al 6061-T6	0.070
ASA FDM	0.050
PETG FDM	0.015

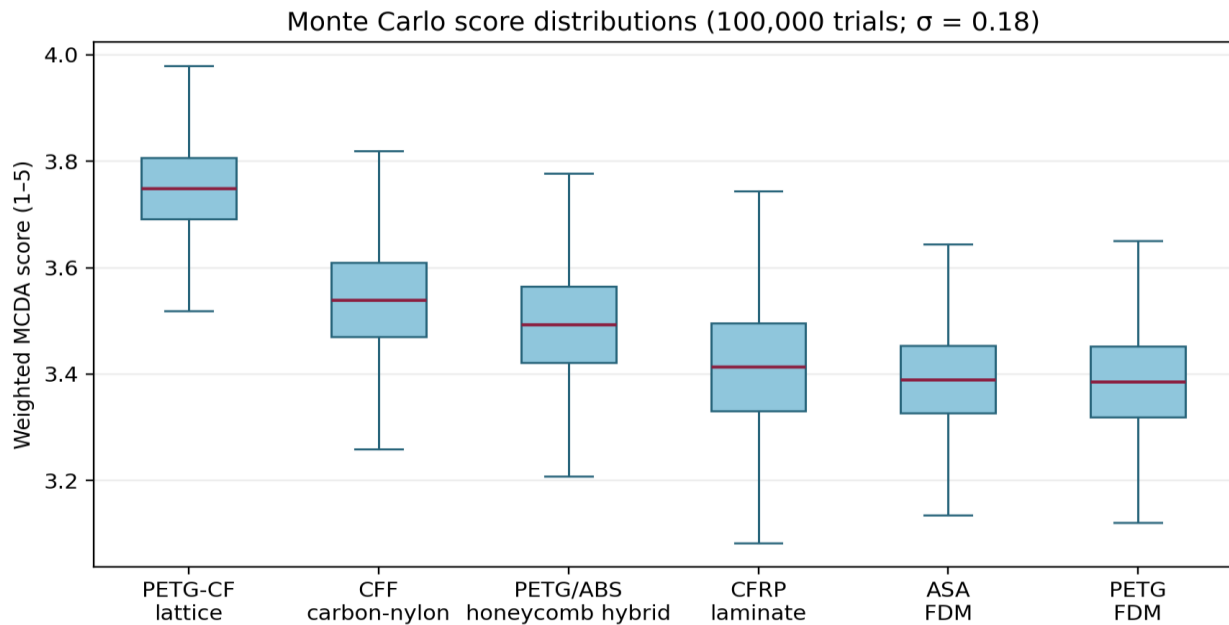


FIGURE 3 Boxplots of simulated weighted scores for the six leading deterministic candidates. Boxes show the interquartile range, centre lines show medians, and whiskers show $1.5 \times \text{IQR}$; outliers are suppressed for readability

Table 17 Baseline Monte Carlo score statistics (100,000 trials; $\sigma = 0.18$; $\alpha = 100$)

Material architecture	Mean score	SD	95% uncertainty interval	First-rank probability
PETG-CF lattice	3.748	0.086	3.579–3.914	93.84%
CFF carbon-nylon	3.539	0.103	3.339–3.744	4.99%
PETG/ABS honeycomb hybrid	3.493	0.105	3.285–3.699	0.32%
CFRP laminate	3.413	0.123	3.174–3.652	0.66%

Table 18 Sensitivity of first-rank probability to score uncertainty

σ (score points)	PETG-CF	CFF carbon-nylon	PETG/ABS hybrid	CFRP	Interpretation
0.10	96.28%	3.24%	<0.10%	0.38%	Narrow uncertainty
0.18	93.84%	4.99%	0.32%	0.66%	Baseline
0.30	85.95%	8.30%	2.53%	1.68%	Wider uncertainty weakens, but does not reverse, the leading probability

The sensitivity analysis revealed that the reference model's preference for the PETG-CF lattice was not affected by $\pm 20\%$ changes in the weights of any individual criterion. A scenario analysis was performed to provide a more meaningful interpretation of the results to a specific decision-maker. It showed that the reference-shells made of PETG-CF lattice were the most balanced designs. However, the alternatives made of CFF carbon-nylon, CFRP, RF-transparent thermoplastics, and Al 6061-T6 would be more desirable if the weights of stiffness, RF continuity, and thermal/fire properties were increased. The scenario, decision-rule, and uncertainty results are detailed in Tables 13-18 and visualized in Figures 2-3.

Table 19 Criterion-level interpretation of leading material families

Material system	Dominant strengths	Design-control issues
PETG-CF lattice	Impact absorption, manufacturability, modular repair, balanced shell role	Thermal/fire performance near batteries; local stiffness limits; score depends on lattice geometry
CFF carbon-nylon	Specific stiffness and strength along designed fiber paths	Fiber orientation, moisture conditioning, RF shielding, and repair complexity
CFRP laminate	High structural efficiency and stiffness-to-mass ratio	RF attenuation, tooling cost, repair/recycling complexity, brittle damage inspection
PETG/ABS honeycomb hybrid	Sacrificial crash absorption and RF transparency	Not a primary load path without skins, ribs, or inserts
ASA FDM	UV/weather resistance and exterior skin function	Moderate stiffness; ribs/inserts required at concentrated loads
PETG FDM	Toughness, printability, RF transparency, repairability	Heat/fire and stiffness limits require design controls
Al 6061-T6	Thermal spreading, threaded interfaces, recyclability	Density, vibration transmission, and RF shielding in continuous enclosures
Mg AZ31	Low-density metal option	Corrosion protection, handling, and fire-risk controls are decisive

5. Discussion

Evidence versus engineering interpretation. The evidence suggests only a mission-qualified prioritization of candidate architectures on a preliminary ordering. The engineering interpretation is that no material should be tasked to perform all shell functions, which is not the same as conventional Ashby screening (focused on property indices) or AHP/TOPSIS-type studies (which identify one aggregated winner). In the present approach, scenario reversals are informative; continuous-fibre architectures win on stiffness-dictated cases, RF-transparent thermoplastics win on enclosure-dictate cases, and aluminium wins on thermal/fire-constrained cases. The model thus effectuates a single-winner ranking into a zoned test plan. The quantitative cross-method testing now demonstrates that the top two candidates are stable across WSM, TOPSIS, and VIKOR, while the lower tiers vary. This separates a robust leading result from method-dependent secondary ordering. Table 19 summarizes the criterion-level strengths and design-control issues of the leading material families.

The preference for PETG-CF lattice in the reference is consistent with literature that printed architecture and infill dominates the mechanical and impact response of relevant drone classes. However, those studies do not establish the present shell or its lattice variant as viable, so the ranking should be regarded as a hypothesis to be fielded to process-matched coupons and instrumented shell drop tests, not imported material properties to a new design.

Carbon fiber conductivity needs to be considered in a compact aircraft with internal or surface antennas, as the uninterrupted shell would detune them via attenuation, impedance mismatch, and pattern distortion. An RF-transparent window would be preferable to an uninterrupted carbon fiber shell for any antennas located at the fuselage or near the surface.

Likewise, the thermal/fire considerations are zonal. The shell would be beneficial as a weather skin, RF window, and crash attenuator, but more localized heat management, screening, spacing, shielding, and dissipation solutions would

be needed for the battery, ESC, motor, and any other high-power or energy-dense components. For this reason, the Al 6061-T6 has a strong reference appeal. Despite not being the lightest shell on average, it has a superior thermal conductivity for heat spreader duties and can be deployed to localize hotspots.

Lifecycle considerations are similarly dependent on the vehicle class. While the production of CFRP may have a higher embodied cost and energy, the reduction of overall structural mass may be leveraged into increased payload, longer endurance, or higher operational altitudes, which would improve the lifecycle emissions of the aircraft. By contrast, the repairability of thermoplastic modules may be beneficial in a high-performance crash class. A true lifecycle analysis would require a common functional unit, a definition of replacement rates, and specific production inventory data for the shortlisted architectures.

The study is thus to be considered as a preliminary design-screening and validation planning tool. The matrix of Table 9 was not physically implemented in the present work. Due diligence requires that the candidate architectures enter the coupon, panel, shell, RF, fire, environmental aging, vibration, finite element analysis, repair, and lifecycle analysis testing before any production readiness can be claimed. With that caveat, the present ranking is a prioritization of test cases rather than an empirical validation.

6. Conclusions

The principal finding is that UAV outer-shell selection is better formulated as a multifunctional architecture problem than as a search for one universally superior material. Under the stated reference assumptions, PETG-CF lattice leads the weighted model (3.758/5), while scenario analysis rationally shifts the preferred architecture toward continuous-fibre composites, RF-transparent polymers, or aluminium as mission priorities change.

The model contributes transparent scoring, explicit design-policy weights, evidence-confidence coding, mission scenarios, one-way sensitivity analysis, and Monte Carlo uncertainty reporting. At $\sigma = 0.18$, PETG-CF ranks first in 93.84% of 100,000 simulations, but this probability describes stability of the model under its assumptions—not the probability that PETG-CF is physically optimal.

The recommended engineering outcome is a hybrid, function-zoned shell: continuous-fibre or CFRP elements for load paths; PETG-CF or PETG/ABS cellular modules for sacrificial impact zones; ASA/PETG for weather skins and RF windows; and metallic inserts or heat spreaders where thermal and threaded-interface demands dominate.

The study is limited by literature-derived and engineering-judgment scores, declared rather than stakeholder-elicited weights, simplified cost indices, independent score perturbations, and the absence of coupon, finite-element, panel, prototype, RF, fire, and field validation. Manufacturing variability is represented only as screening uncertainty and not by process-specific statistical distributions.

Future work should (i) test matched-process coupons and representative shell zones; (ii) validate impact and modal behaviour by finite-element analysis and instrumented prototype tests; (iii) measure RF attenuation and battery-adjacent fire/thermal response; (iv) obtain volume-specific manufacturing quotations and lifecycle inventories; (v) elicit weights from a multidisciplinary stakeholder panel; and (vi) compare WSM rankings with TOPSIS, VIKOR, PROMETHEE, and ELECTRE, including correlated and process-specific uncertainty models.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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